Higgs Boson Mass and Couplings Measurements at the LHC

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On behalf of ATLAS and CMS

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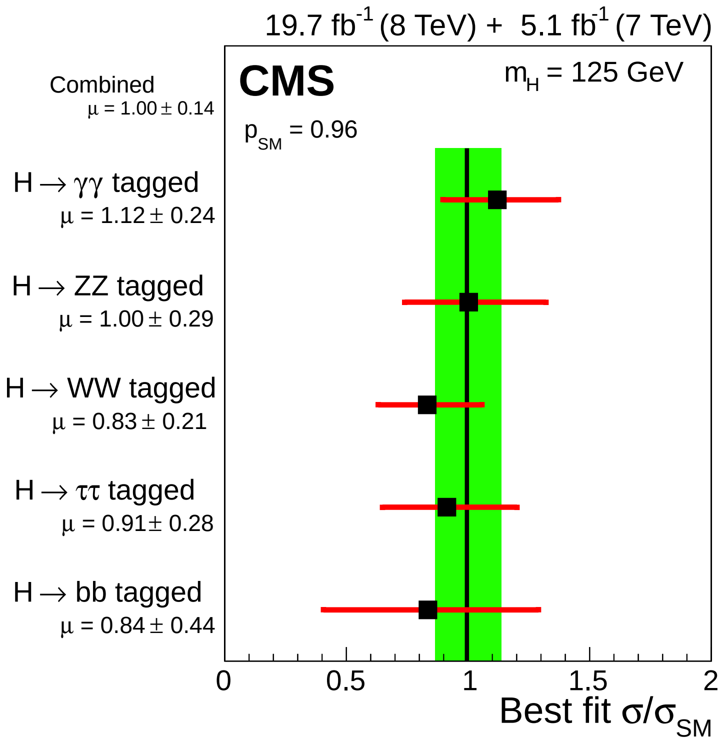
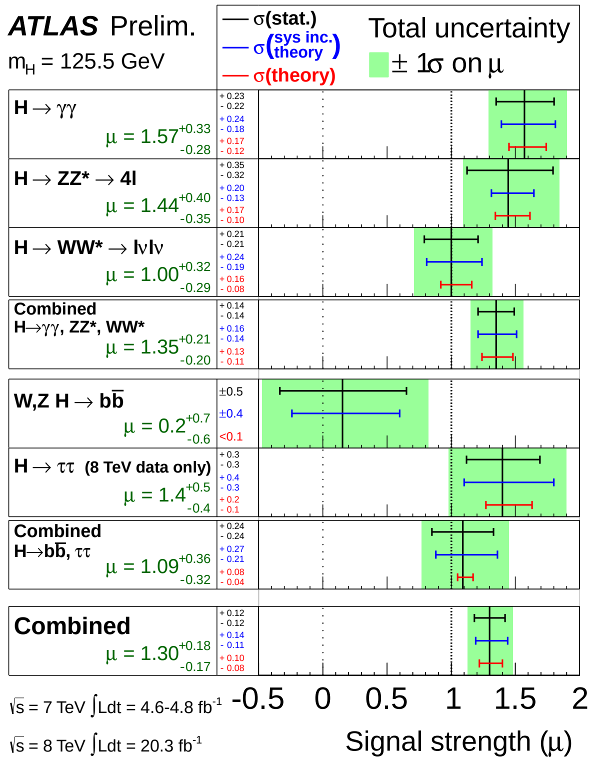
Latest results

Result	ATLAS	CMS
$H \to \gamma\gamma$	29 Aug '14	2 Jul '14
$H \to ZZ^*$	22 Aug '14	18 Dec '13
$H \to WW^*$	8 Dec '14	4 Dec '13
$H \to b\bar{b}$	22 Sep '14	14 Oct '13
$H \to \tau^+\tau^-$	20 Jan '15	20 Jan '14
Couplings	20 Mar '14	14 Dec '14
Mass	15 Jun '14	14 Dec '14
Off-shell	3 Mar '15	14 May '14
Spin	4 Jul '13	14 Nov '14

- Legacy spin and couplings combination from ATLAS coming soon
  - Current couplings combination using inputs older than shown above!
- ATLAS+CMS combination underway. Mass out soon, couplings later
- ATLAS off-shell result released just a few days ago

At a glance

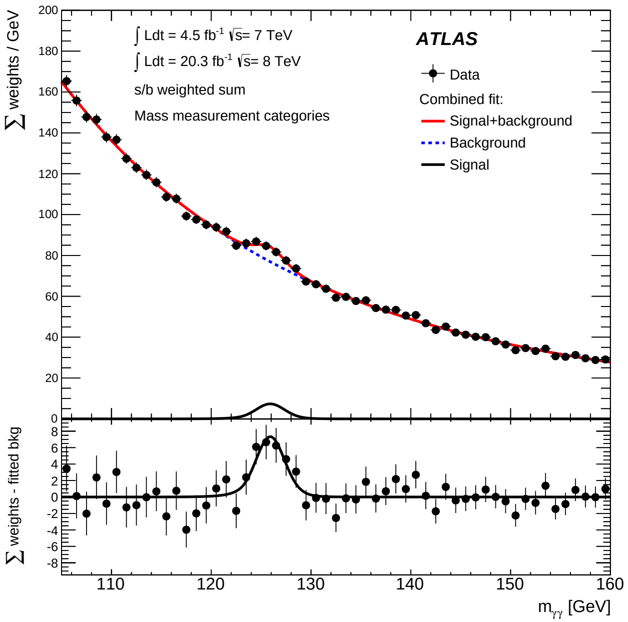


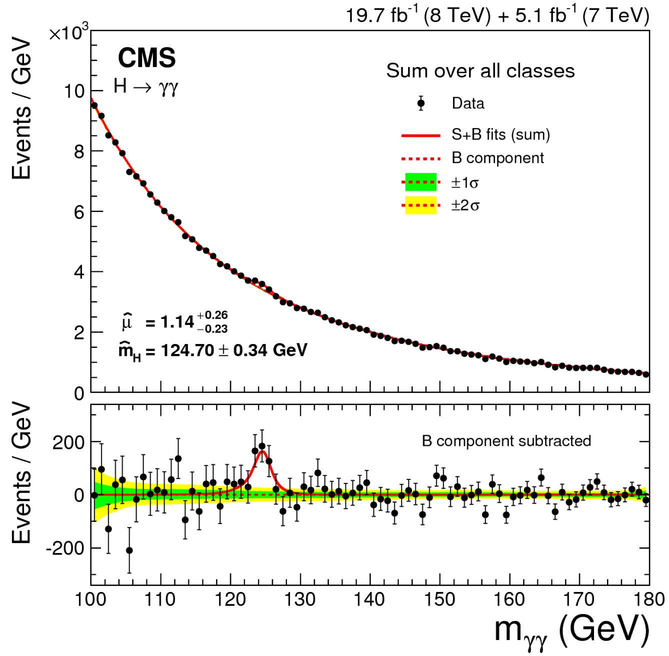


- Quick overview of results from individual channels
- Measurement of global μ that scales all modes wrt SM
  - Not a well motivated BSM scenario!
  - More targeted parametrizations shown later

Mass

Mass in $H \to \gamma\gamma$

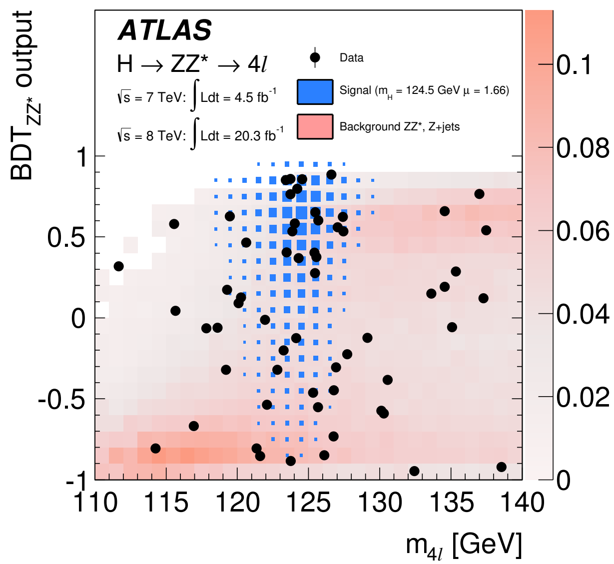




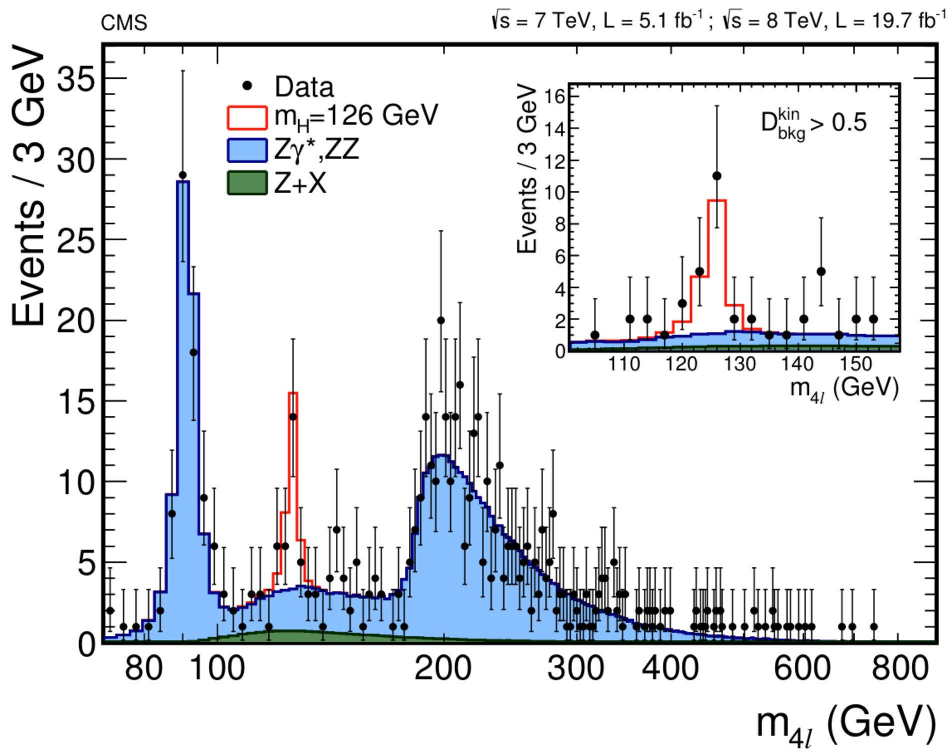
- Event categorization based on conv. / unconv. photons, η_γ, etc.
  - 10 categories for each 7- and 8-TeV
- Analytical fit to diphoton mass spectrum
  - Bkg: Expo. of 1^{st} or 2^{nd} order poly
  - Signal: Crystal Ball + Gaus

- Diphoton BDT categorization
  - Depends on di-γ reso., S vs B kinematics
- Some production-based tagging ($\sim$1% of evts)
- Signal modelled as a sum of Gaussians
- Several bkg models considered

Mass in $H \to ZZ^*$

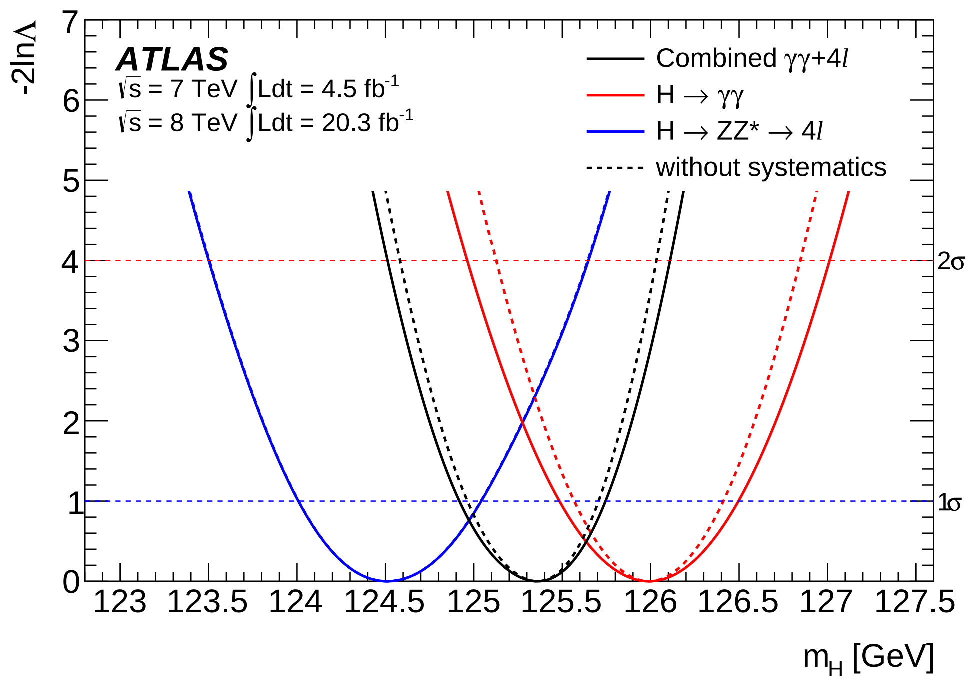


- ZZ^* bkg sim @NLO, dd $t\bar{t}$ and Z+jets
- Semi-analytical signal (kernel density estimation)
- 2D fit to $m_{4\ell} \times \mathcal{O}_{\mathrm{BDT}_{ZZ^*}}$
  - m_{4l} between 110-140 GeV
  - BDT helps discriminate against ZZ^*
  - Separated by $4e$, 4μ, $2e2\mu$, $2\mu2e$



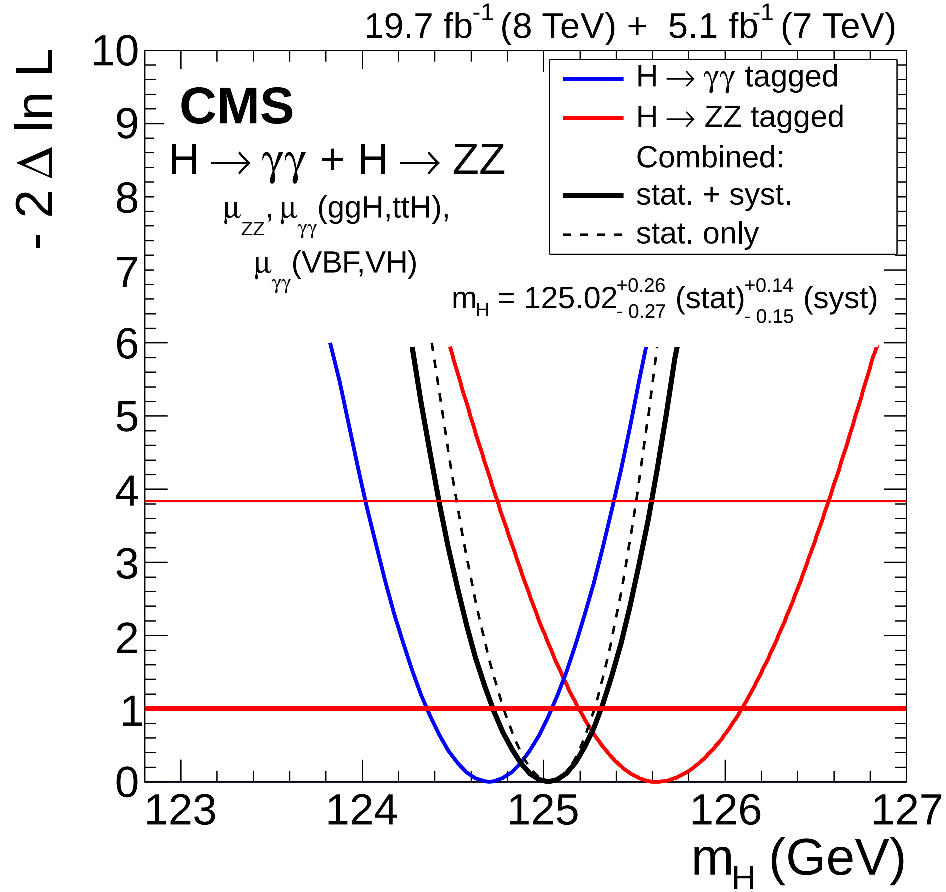
- Categorization by $4e$, 4μ, $2e2\mu$, $2\mu2e$
  - Also by jet multiplicity and $p_T^{4\ell}$ for ggF, VBF, and VH tagging
- 3D fit to m_{4l}, angular variables, and evt-by-evt mass resolution used to determine mass

Mass Measurement



	$H \to ZZ^{(*)} \to \ell\ell\ell\ell$	$H \to \gamma\gamma$
$\hat{m}_H$ (GeV)	$124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{sys})$	$125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{sys})$

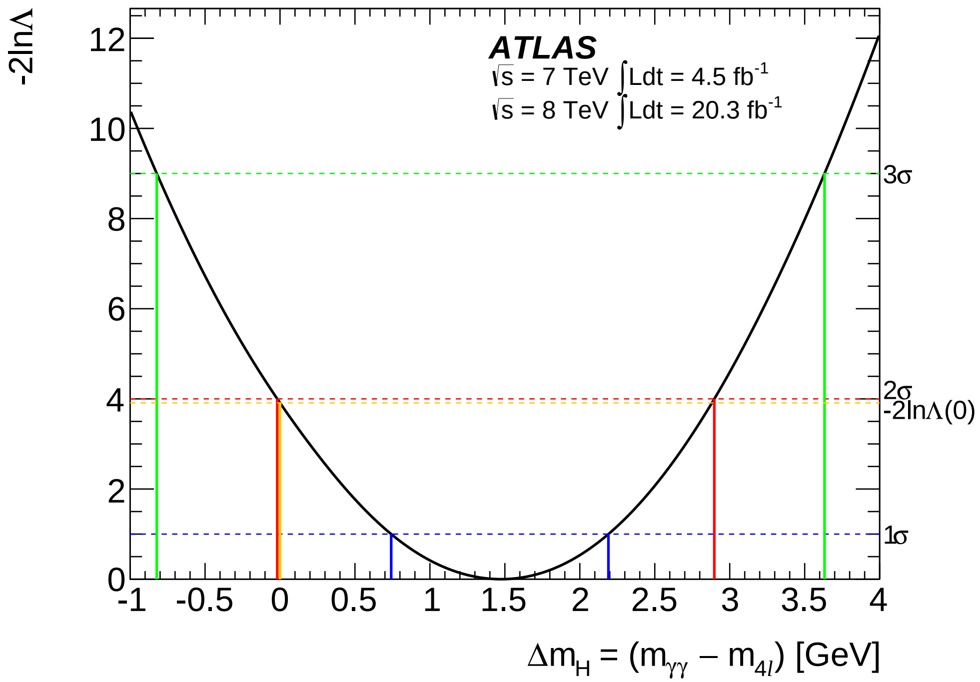
Combined mass: $125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})$

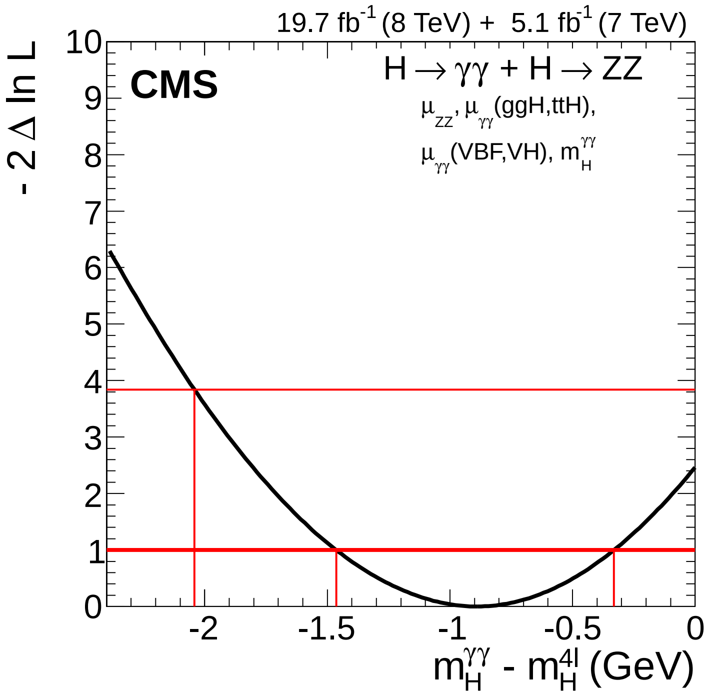


	$H \to ZZ^{(*)} \to \ell\ell\ell\ell$	$H \to \gamma\gamma$
$\hat{m}_H$ (GeV)	$125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{sys})$	$124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{sys})$

Combined mass: $125.02 \pm 0.27(\text{stat}) \pm 0.15(\text{sys})$

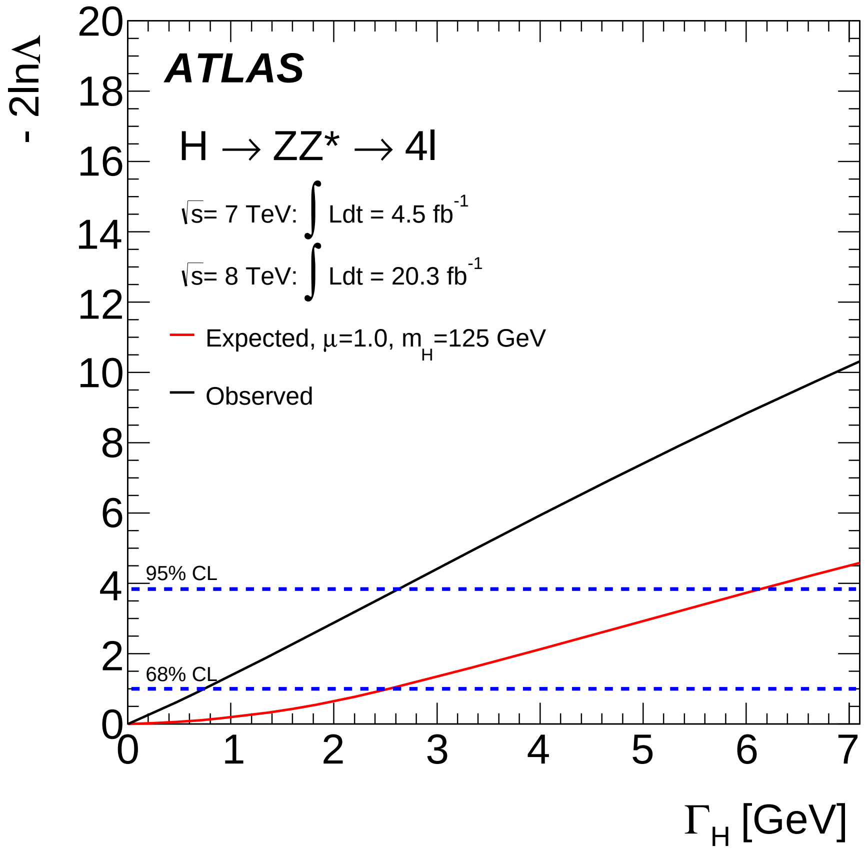
Mass Compatibility

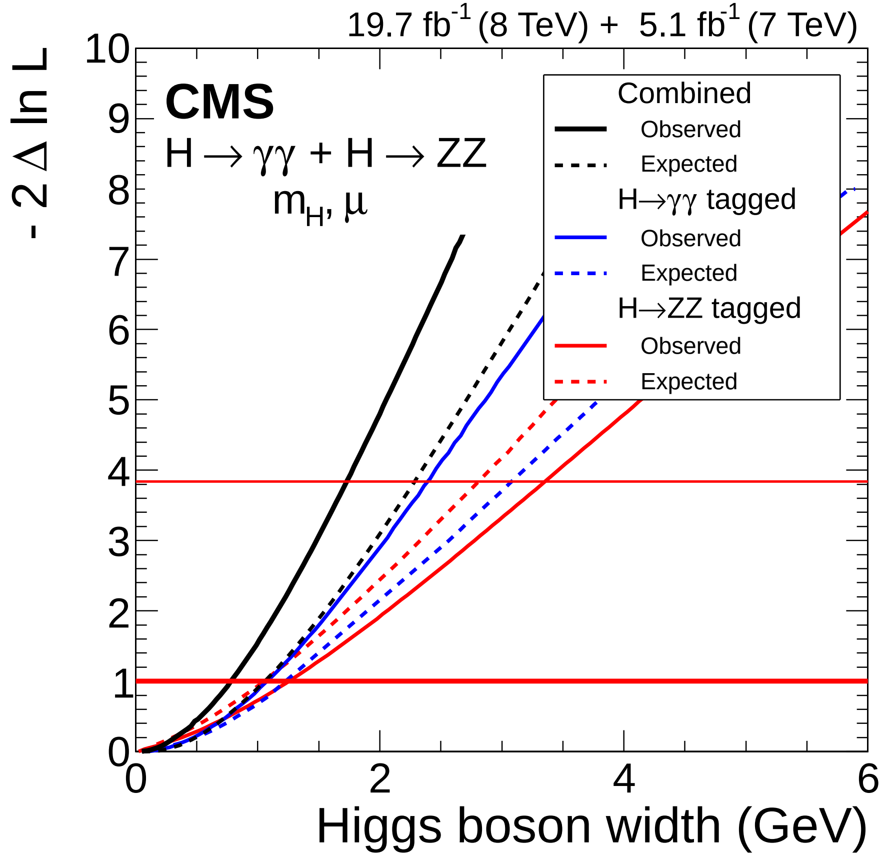




- Distinguish $m_H^{\gamma\gamma}$ and $m_H^{4\ell}$, and define $\Delta m_H \equiv m_H^{\gamma\gamma} - m_H^{4\ell}$
  - Test statistic is $q_0 = -2\ln\Lambda(\Delta m_H = 0)$
- Masses are compatible at 2σ level in ATLAS, 1.6σ in CMS
  - Big effort to reduce energy scale systematics in ATLAS by improving egamma calibration
  - Discrepancy down from 3σ in first measurement and 2.5σ in 2013

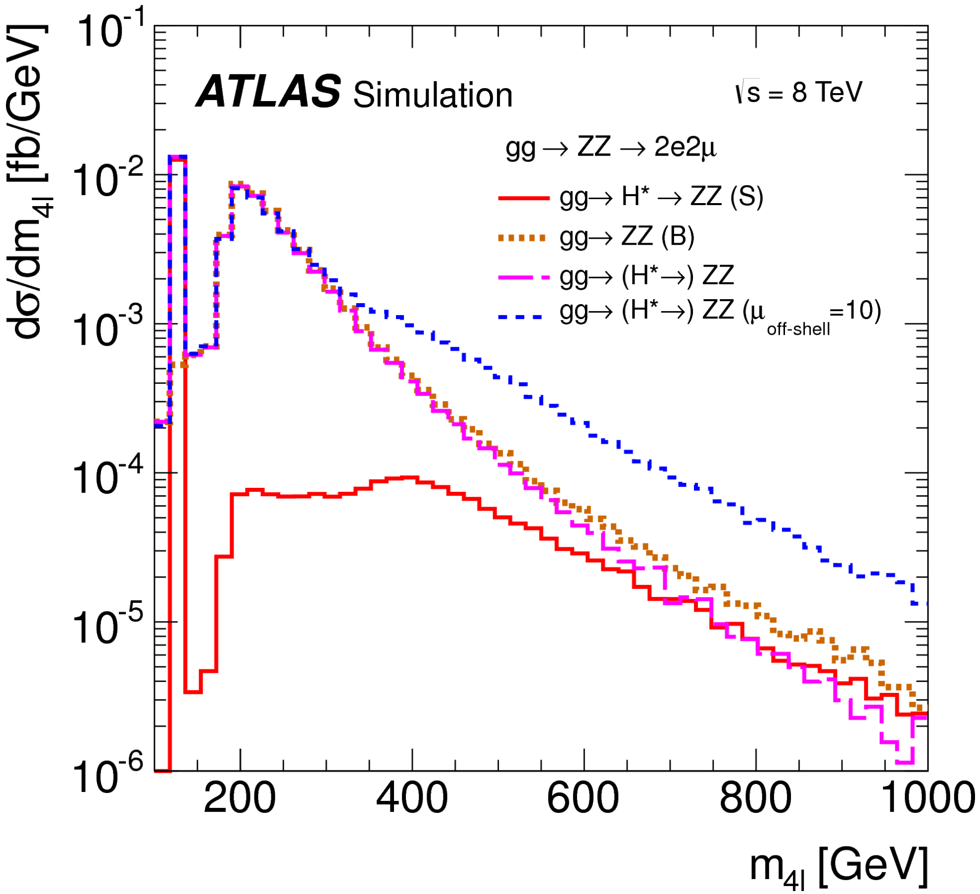
Width





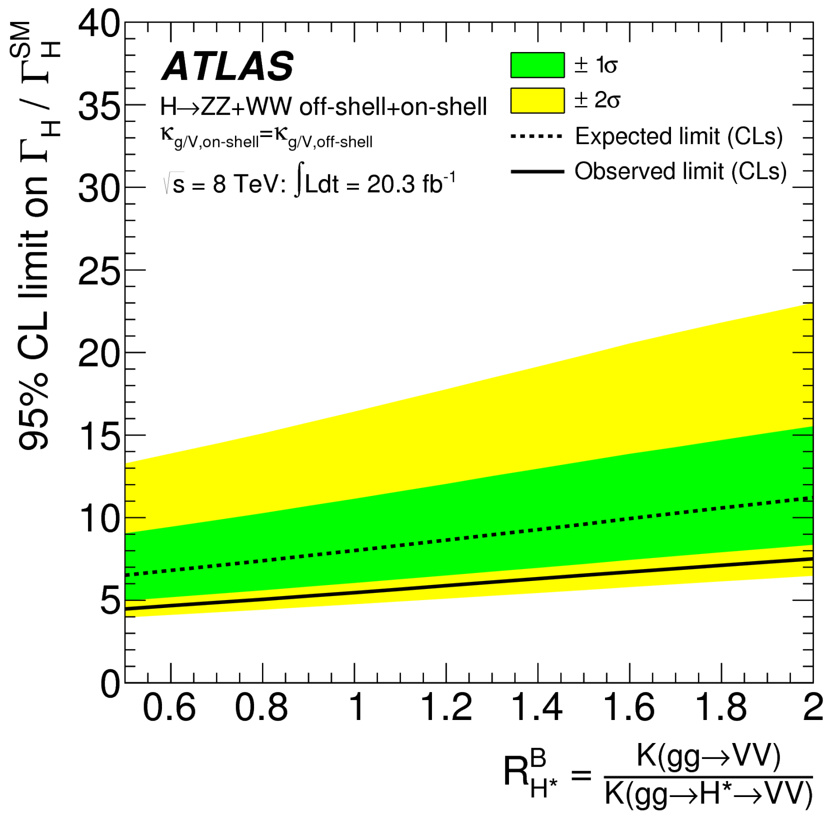
- Direct limits on the total width can be made, but very far from reaching SM sensitivity
  - ATLAS 95%: $\Gamma_H < 2.6$ GeV
  - CMS 95%: $\Gamma_H < 1.7$ GeV

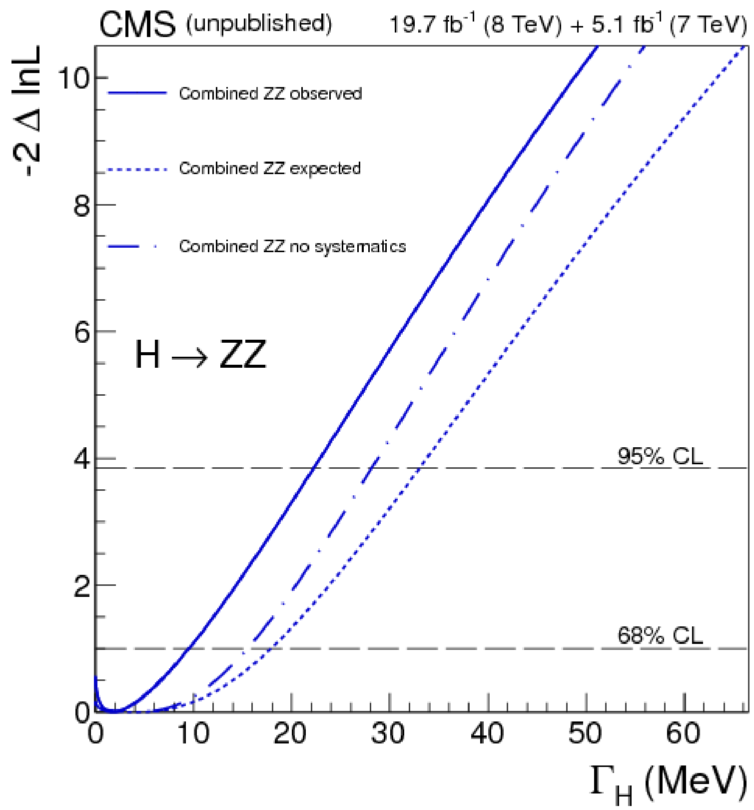
Off-shell Width Measurement



- Access to total width indirectly through high-mass off-peak regions above $2m_V$ in VV channels
  - $\frac{\sigma^{gg\to H^*\to VV}_{\mathrm{off-shell}}}{\sigma^{gg\to H^*\to VV}_{\mathrm{off-shell,SM}}} = \kappa^2_{g,\mathrm{off-shell}}\kappa^2_{V,\mathrm{off-shell}}$
  - $\frac{\sigma^{gg\to H\to VV}_{\mathrm{on-shell}}}{\sigma^{gg\to H\to VV}_{\mathrm{on-shell}}} = \frac{\kappa^2_{g,\mathrm{on-shell}}\kappa^2_{V,\mathrm{on-shell,SM}}}{\frac{\Gamma_H}{\Gamma_H^{SM}}}$
- Assuming on-off-shell universality of $\kappa_{g,V}$ gives measurement of $\frac{\Gamma_H}{\Gamma_H^{SM}}$
- Plot demonstrates effect on invariant mass of increasing off-shell coupling by 10x

Off-shell Width Measurement





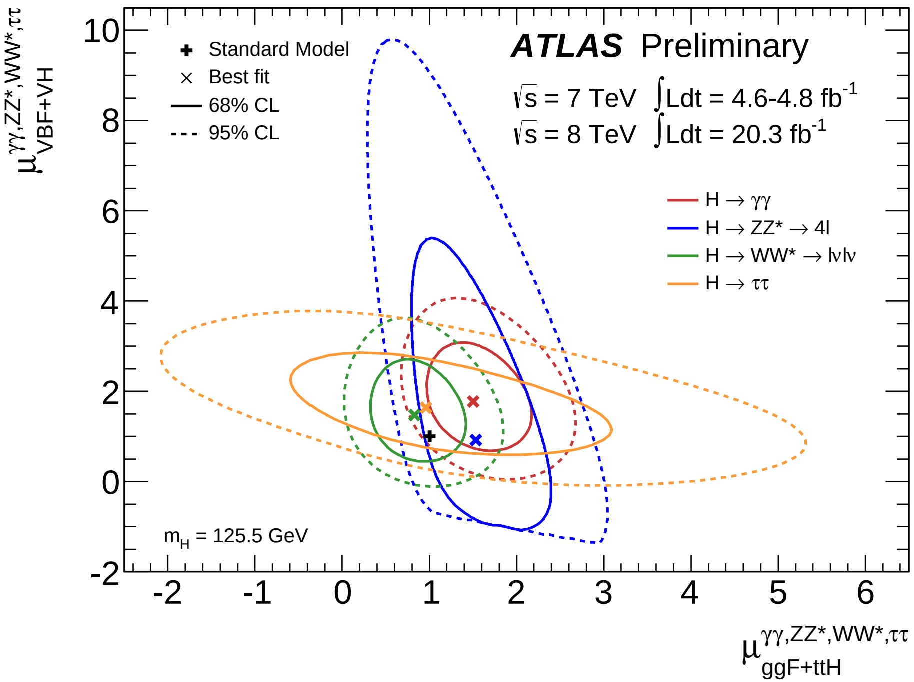
- ATLAS 95% CL$_s$: $\Gamma_H/\Gamma_H^{SM} < 4.8 - 7.7$ (varying $gg \to VV$ K-factor between 0.5-2x)
- CMS 95% CL$_s$: $\Gamma_H/\Gamma_H^{SM} < 5.4$
  - $gg \to ZZ$ K-factor included as a systematic

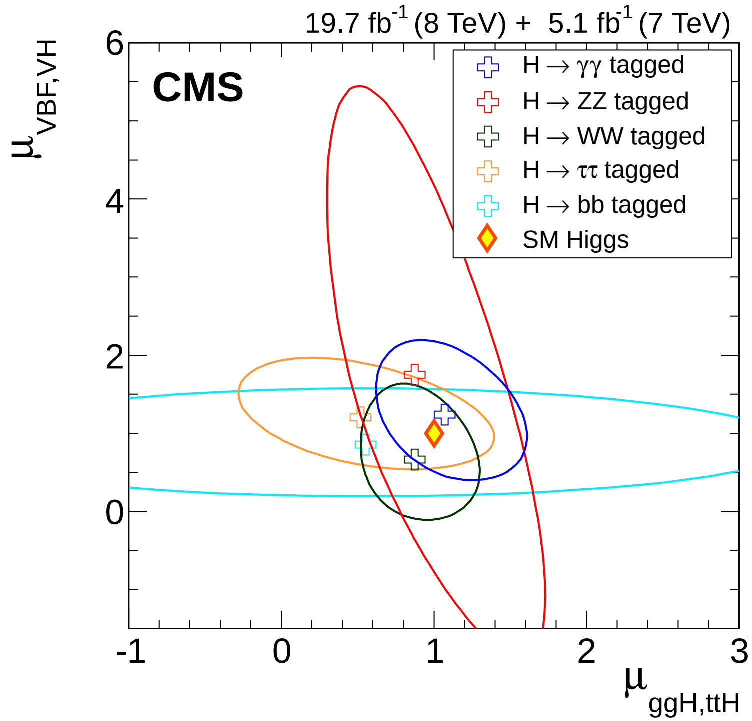
Properties

Signal Parametrization

- Assumptions for properties measurements
  - CP even scalar
  - Single resonance: same boson in all channels
  - Narrow width: $(\sigma \times \mathcal{B})(ii \to H \to ff) = \sigma_{ii} \cdot \frac{\Gamma_{ff}}{\Gamma_H}$
- $n^k_{\mathrm{Signal}} = \left(\sum \mu_i \sigma_{i,SM} \times A^k_{if} \times \varepsilon^k_{if}\right) \times \mu_f \mathcal{B}_{f,SM} \times \mathcal{L}^k$
  - $\sigma_i = \mu_i \sigma_{i,SM}$ is the i^{th} hypothesized production cross section
  - $\mathcal{B}_f = \mu_f \mathcal{B}_{f,SM}$ is the f^{th} hypothesized branching fraction
  - Detector acceptance A^k_{if}, reconstruction efficiency ε^k_{if}, and integrated luminosity $\mathcal{L}^k$ are fixed by above assumptions
- Fixing μ ratios to SM may conceal tension between data and SM
  - Separate signal contributions from different modes

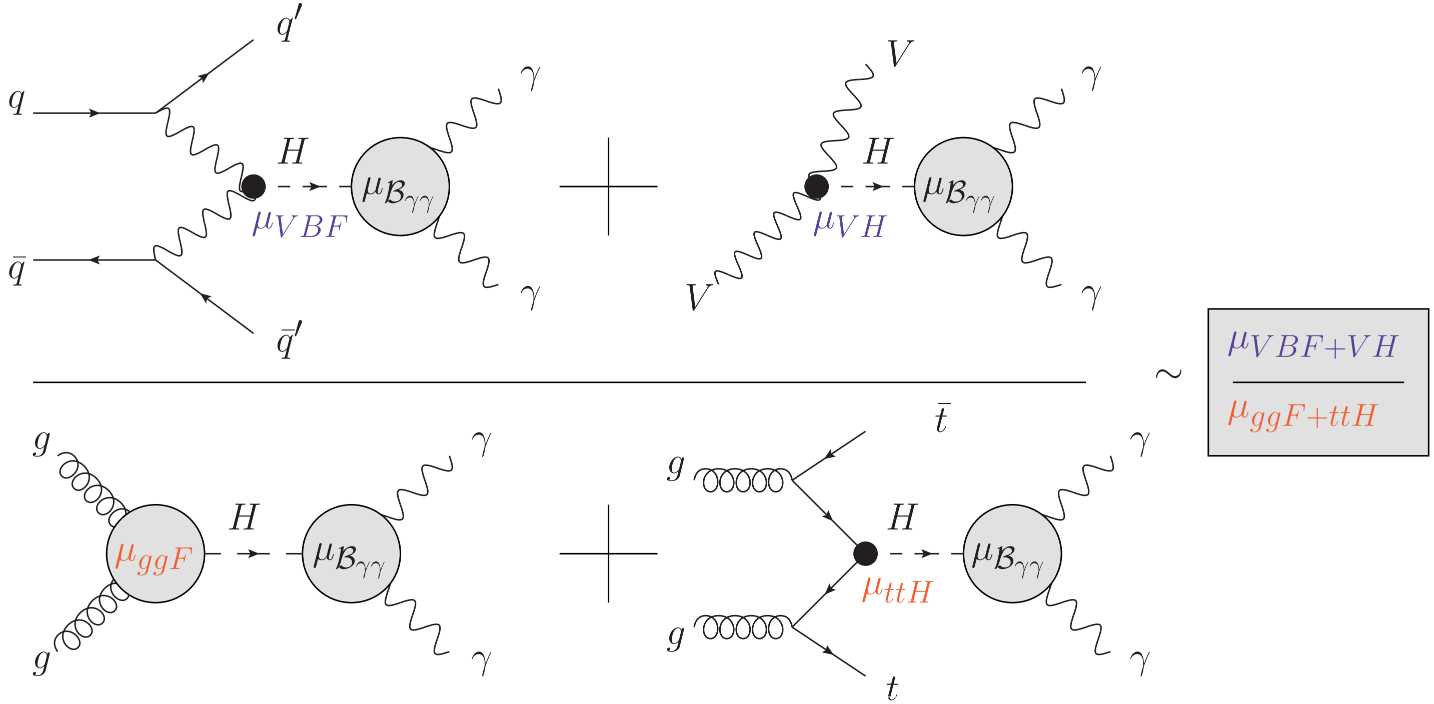
Contour by Production





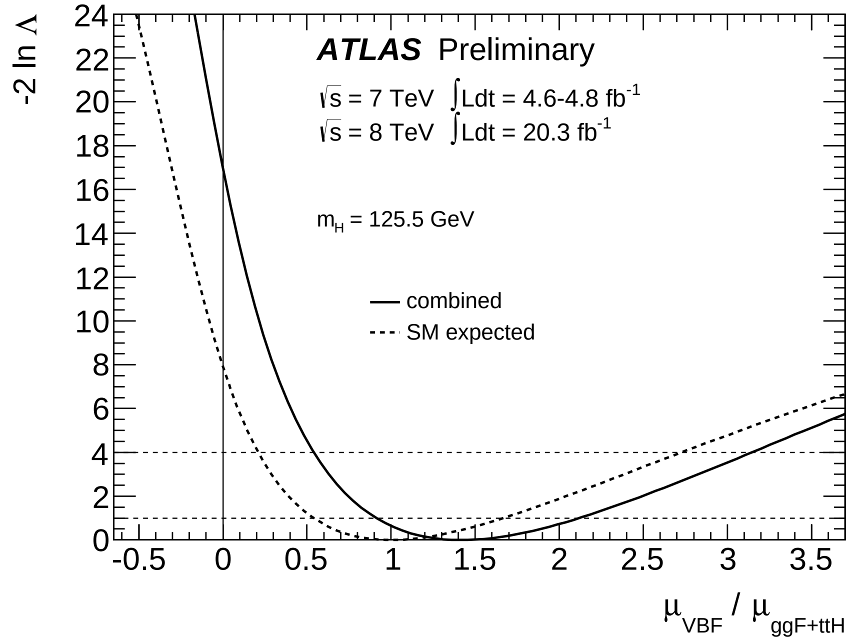
- Disentangle production for each decay mode by adding categories sensitive to each
- Implicit factor of $\mu_{BR(H\to XX)}$ in each axis that is fully degenerate with production normalizations
  - Different decays in each channel means combined contour can't be produced in this way

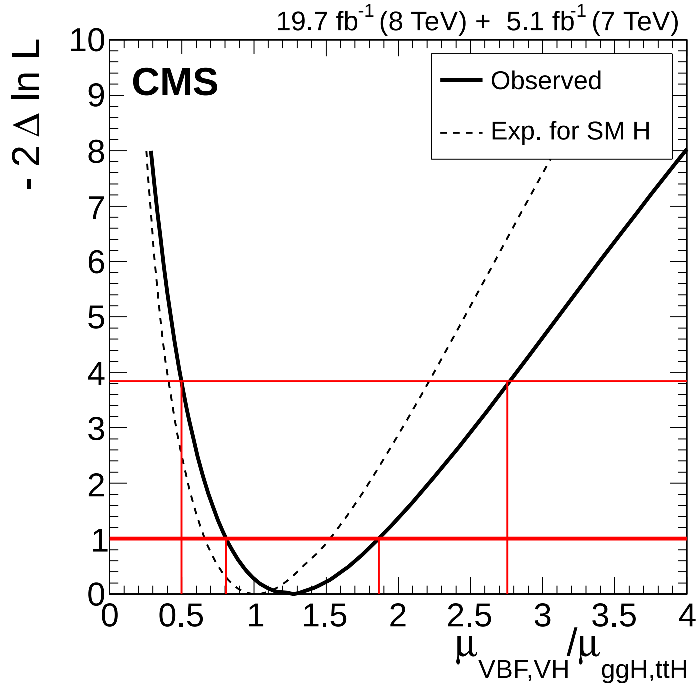
Parametrization by Production Mode



- Simple case: Decouple VBF+VH and ggF+ttH production modes
- $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$ is a statement purely about Higgs production
  - Branching ratio cancels in ratio for each channel→can combine measurements
- Explore likelihood with this ratio as a parameter of interest

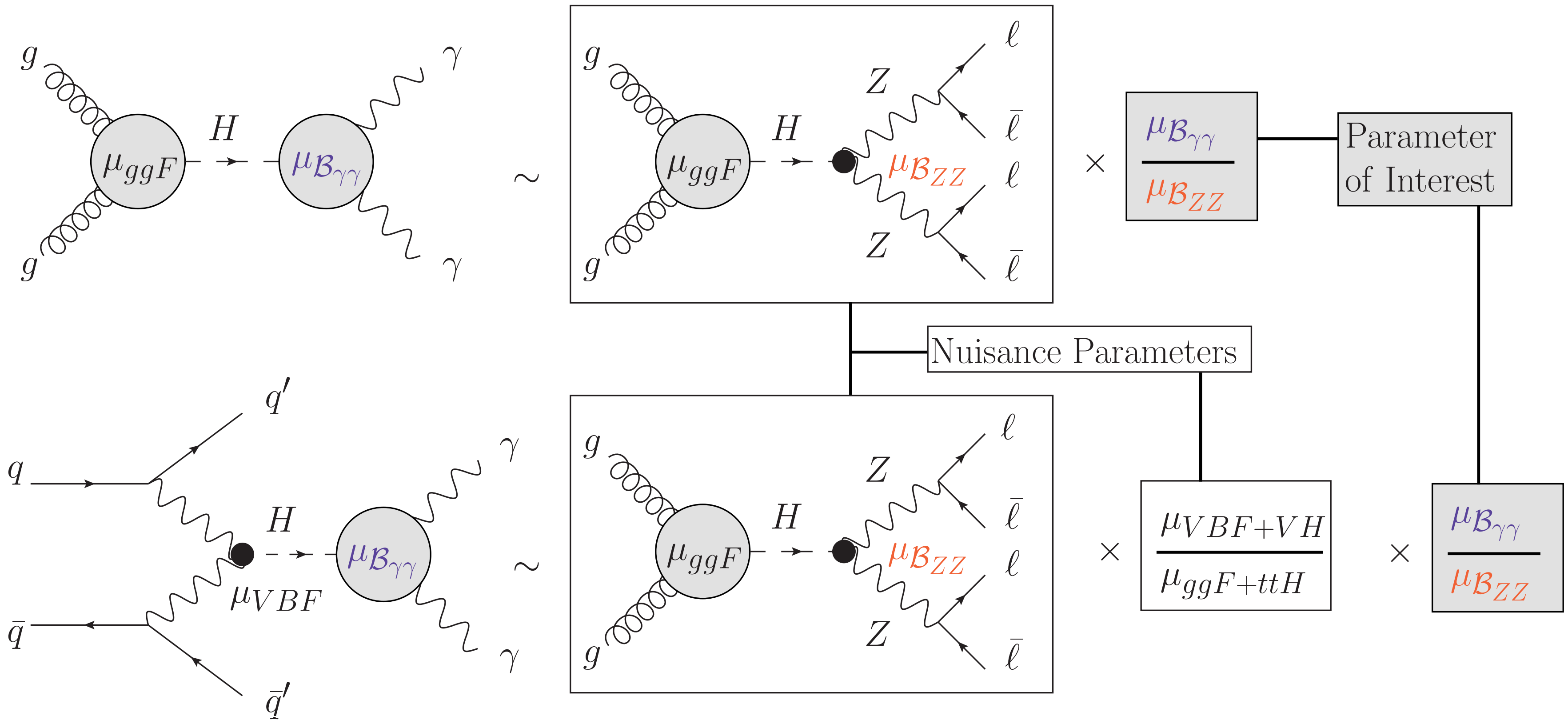
Testing for VBF Production





- $-2\ln\Lambda(\mu_{VBF} = 0)$ tests statistical significance of Higgs production through vector bosons
  - ATLAS: $\rightarrow$ 4.1σ observed (2.8σ expected)
  - CMS: $\rightarrow$ 3.7σ observed (3.3σ expected)

Parametrizing by Decay Mode



- Similar to production parametrization, a Parameter of Interest (POI) can be defined that is purely a statement about Higgs decay
  - Can be done for all combinations of branching ratios: $\lambda_{xx,yy}$ $(xx, yy = \{\gamma\gamma, ZZ, WW, \tau\tau, bb\})$
- Large ggF uncertainties cancel in ratio, but statistical uncertainties grow

Ratios of Decay Modes

Double ratio measurements of branching fractions (CMS)

Best fit $\lambda_{\mathrm{col,row}}$	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau^+\tau^-$	$H\to b\bar{b}$
$H\to\gamma\gamma$	1	$0.92^{+0.38}_{-0.27}$	$0.83^{+0.27}_{-0.22}$	$0.71^{+0.43}_{-0.25}$	$0.63^{+0.44}_{-0.35}$
$H\to ZZ^*$	$1.06^{+0.44}_{-0.31}$	1	$0.88^{+0.38}_{-0.26}$	$0.76^{+0.43}_{-0.30}$	$0.65^{+0.59}_{-0.37}$
$H\to WW^*$	$1.21^{+0.41}_{-0.31}$	$1.10^{+0.44}_{-0.33}$	1	$0.86^{+0.42}_{-0.32}$	$0.74^{+0.61}_{-0.41}$
$H\to\tau^+\tau^-$	$1.41^{+0.75}_{-0.45}$	$1.31^{+0.81}_{-0.48}$	$1.15^{+0.68}_{-0.44}$	1	$0.87^{+0.69}_{-0.49}$
$H\to b\bar{b}$	$1.60^{+1.86}_{-0.70}$	$1.48^{+1.85}_{-0.70}$	$1.32^{+1.57}_{-0.59}$	$1.14^{+1.34}_{-0.52}$	1

- Tabulated results for each pair of decay modes from CMS
  - Similar ATLAS results coming soon! Previous results from 2013:
    - $\lambda_{\gamma\gamma,ZZ} = 1.1^{+0.4}_{-0.3}$
    - $\lambda_{\gamma\gamma,WW} = 1.7^{+0.7}_{-0.5}$
    - $\lambda_{ZZ,WW} = 1.6^{+0.8}_{-0.5}$
- No significant deviations from SM

Couplings

"Kappa Model" - LO Coupling Parametrization

Production modes

$$\frac{\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\sigma_{\mathrm{ttH}}}{\sigma_{\mathrm{ttH}}^{\mathrm{SM}}} = \kappa_t^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}}}{\Gamma_{\mathrm{WW}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\Gamma_{\mathrm{ZZ}}}{\Gamma_{\mathrm{ZZ}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{\mathrm{SM}}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Handling Undetectable Modes

Currently undetectable decay modes

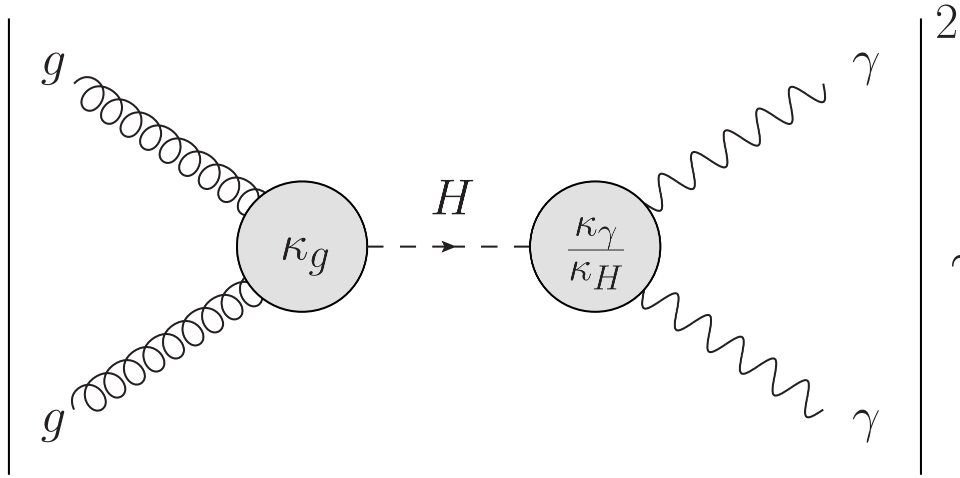
$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}} = \begin{cases} \kappa^2_{(H\to gg)}(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

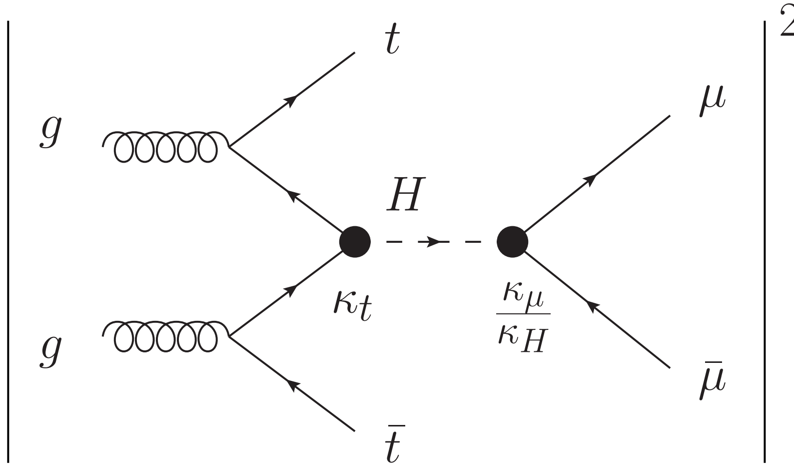
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{\mu\mu}^{\mathrm{SM}}} = \kappa_\tau^2$$



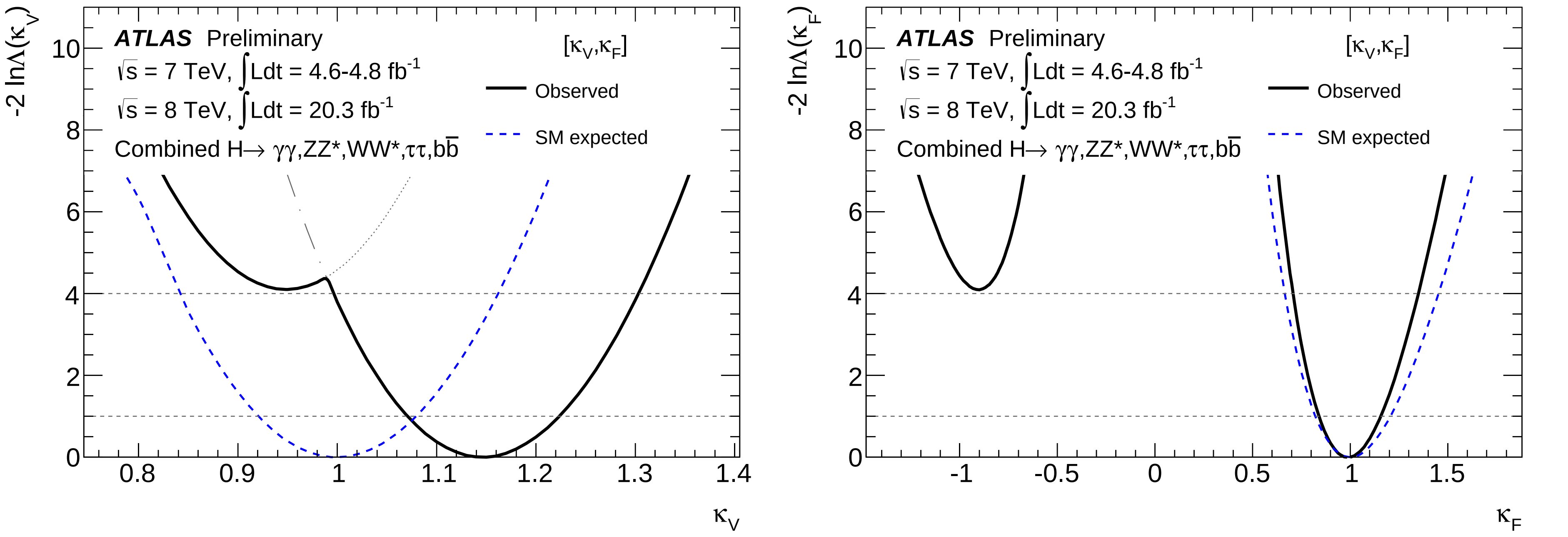
$$\sim \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$



$$\sim \frac{\kappa_t^2 \kappa_\mu^2}{\kappa_H^2} \longrightarrow \frac{\kappa_t^2 \kappa_\tau^2}{\kappa_H^2}$$

- Fix undetectable decay modes by measurable couplings

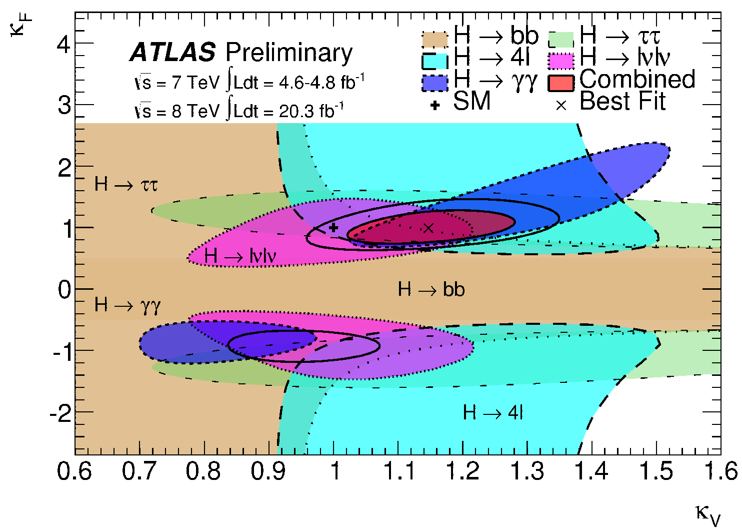
Vector vs Fermion

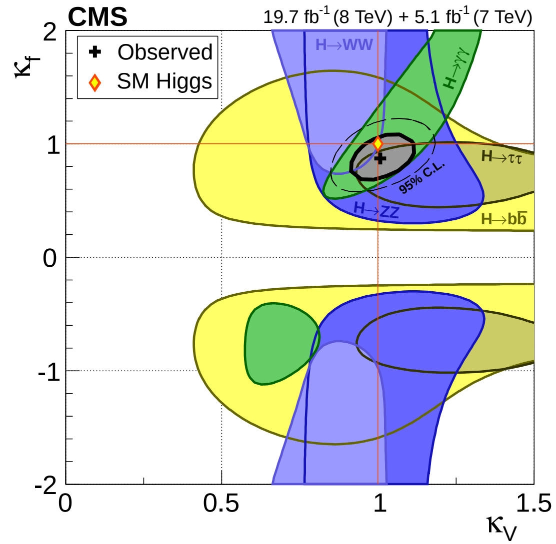


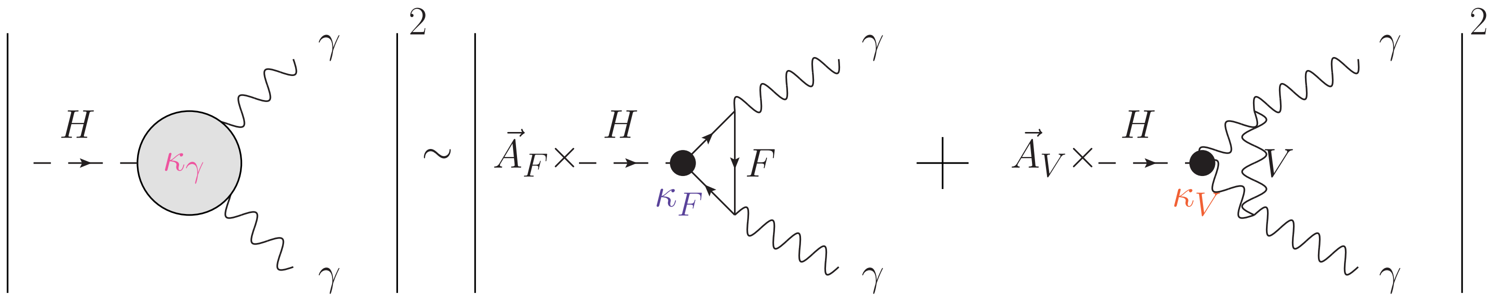
- Test Fermion vs Vector coupling compatibility with SM
- Assume only SM particles enter total width and $H \to \gamma\gamma$, $gg \to H$ loops

Parameter	ATLAS	CMS
$\kappa_F (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_g)$	0.99±0.17	0.87±0.14
$\kappa_V (= \kappa_W = \kappa_Z)$	1.15±0.08	1.01±0.07

Interference



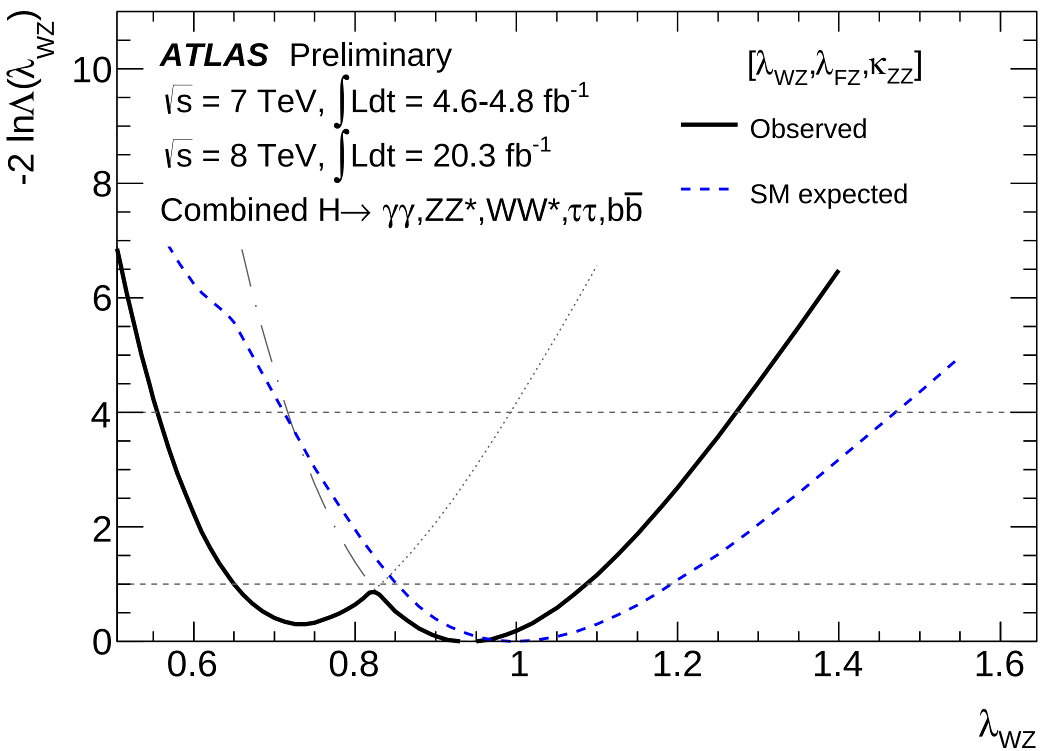


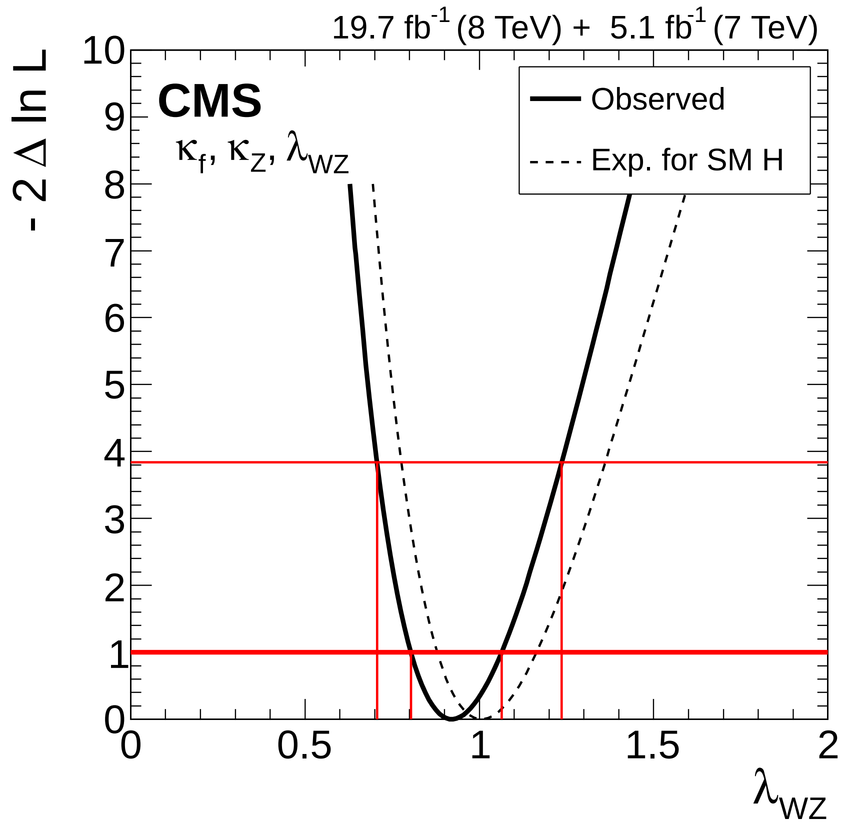


$$\kappa_\gamma^2 \sim 0.07\,\kappa_F^2 - 0.66\,\kappa_F\kappa_V + 1.59\,\kappa_V^2$$

- Two minima in likelihood due to V/F interference within $H \to \gamma\gamma$ loop

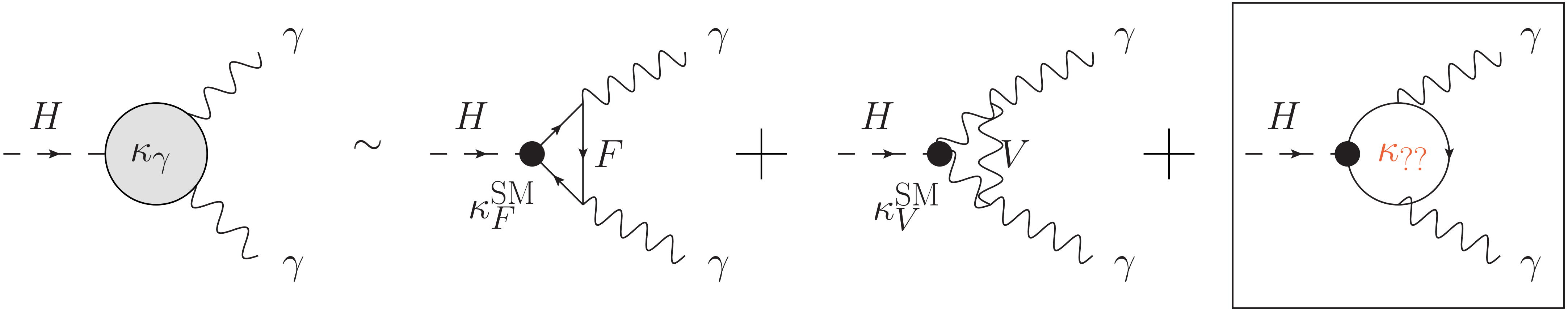
Custodial Symmetry





- Identical coupling scale factors for W and Z bosons (custodial symmetry) has strong theoretical and experimental bounds: Test it in the Higgs sector!

Probing non-SM Loop Contributions

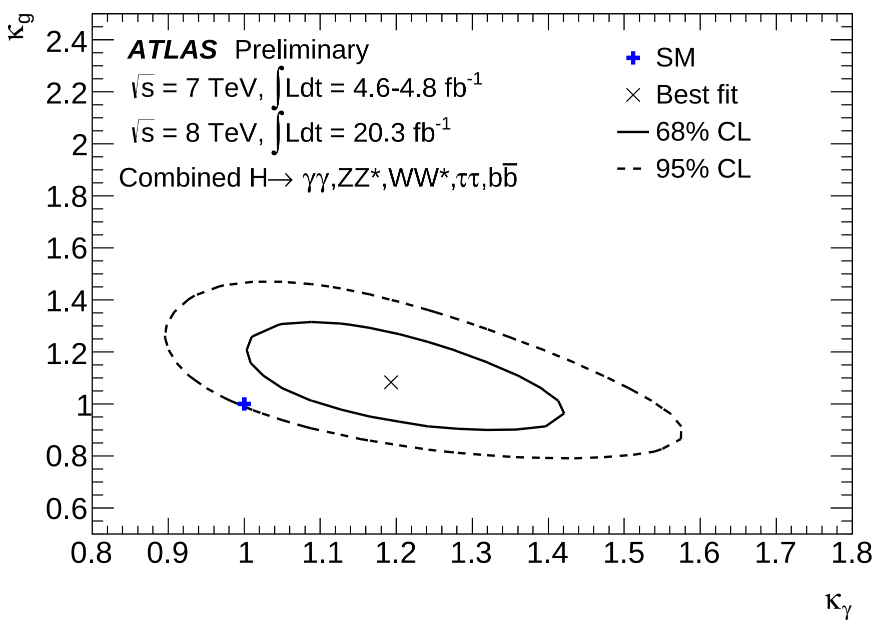


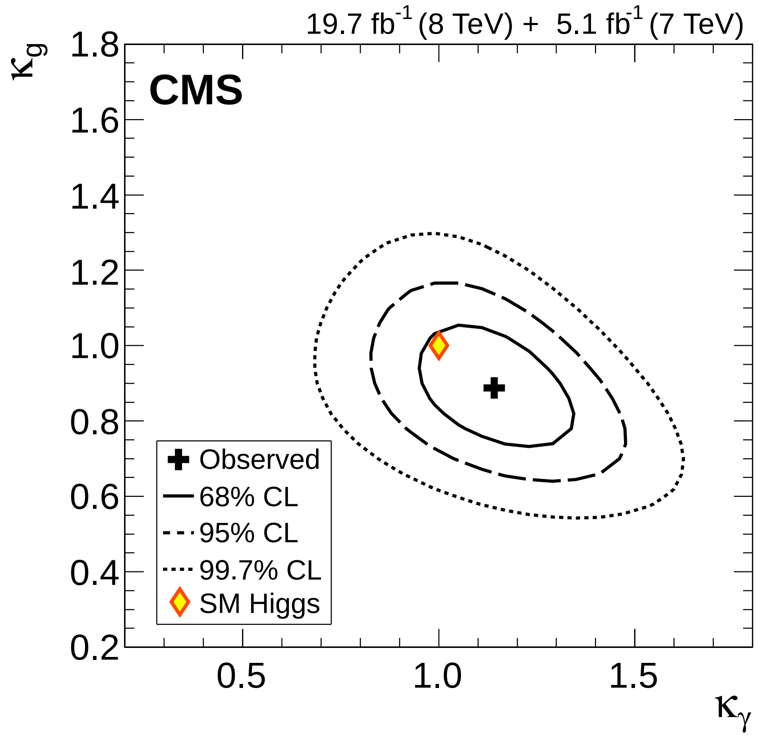
Vertex Loop Models

Model	Free Parameters	Example
SM only in Total Width	κ_g κ_γ	$\sigma(gg \to H) \cdot \mathcal{B}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \kappa_\gamma^2}{0.085\kappa_g^2 + 0.0023\kappa_\gamma^2 + 0.91}$
Free Total Width	κ_g κ_γ $\mathrm{BR}_{\mathrm{inv.,undet.}}$	$\sigma(gg \to H) \cdot \mathcal{B}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \kappa_\gamma^2 \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})}{0.085\kappa_g^2 + 0.0023\kappa_\gamma^2 + 0.91}$

- Fix all non-loop κ_i to SM value of 1
- Directly measure effective couplings to test for non-SM contributions
- Put limit on decays to invisible and undetectable modes

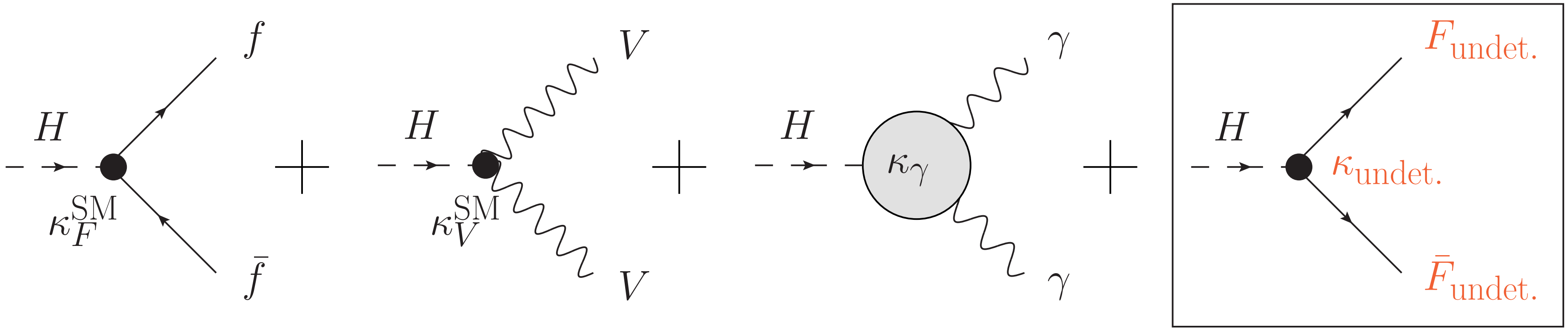
SM only in Total Width

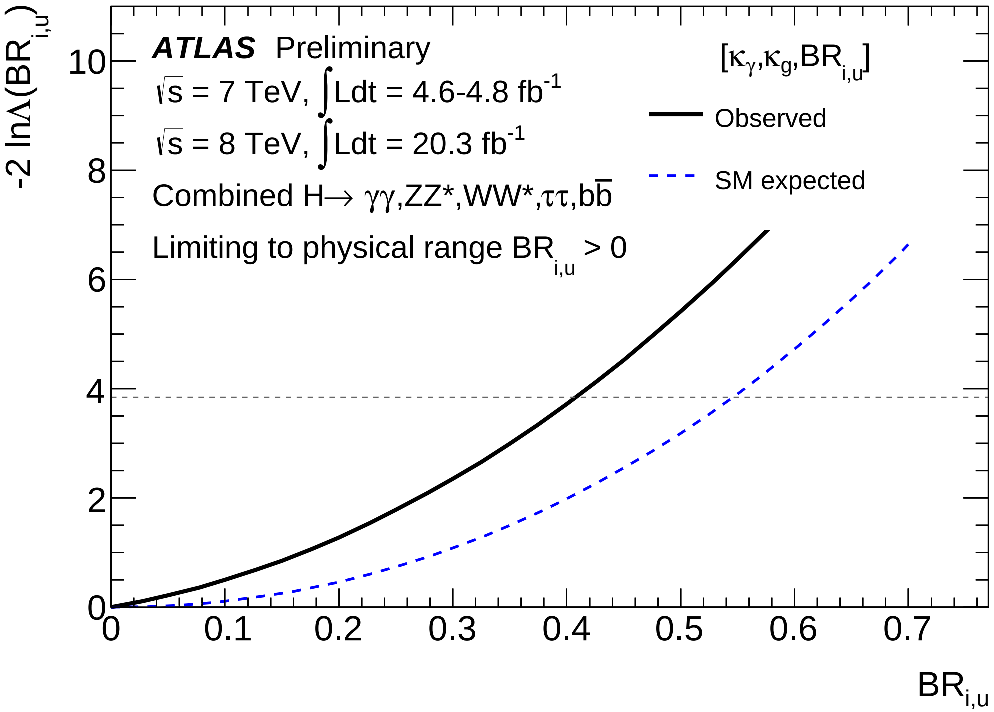




- $\sigma(gg \to H) \cdot \mathcal{B}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \kappa_\gamma^2}{0.085\kappa_g^2 + 0.0023\kappa_\gamma^2 + 0.91}$
- Are non-SM particles in the $gg \to H$ or $H \to \gamma\gamma$ loops?
  - $\kappa_g = 1.08 \pm 0.13$ (ATLAS), 0.89 ± 0.11 (CMS)
  - $\kappa_\gamma = 1.19^{+0.15}_{-0.12}$ (ATLAS), 1.14 ± 0.13 (CMS)

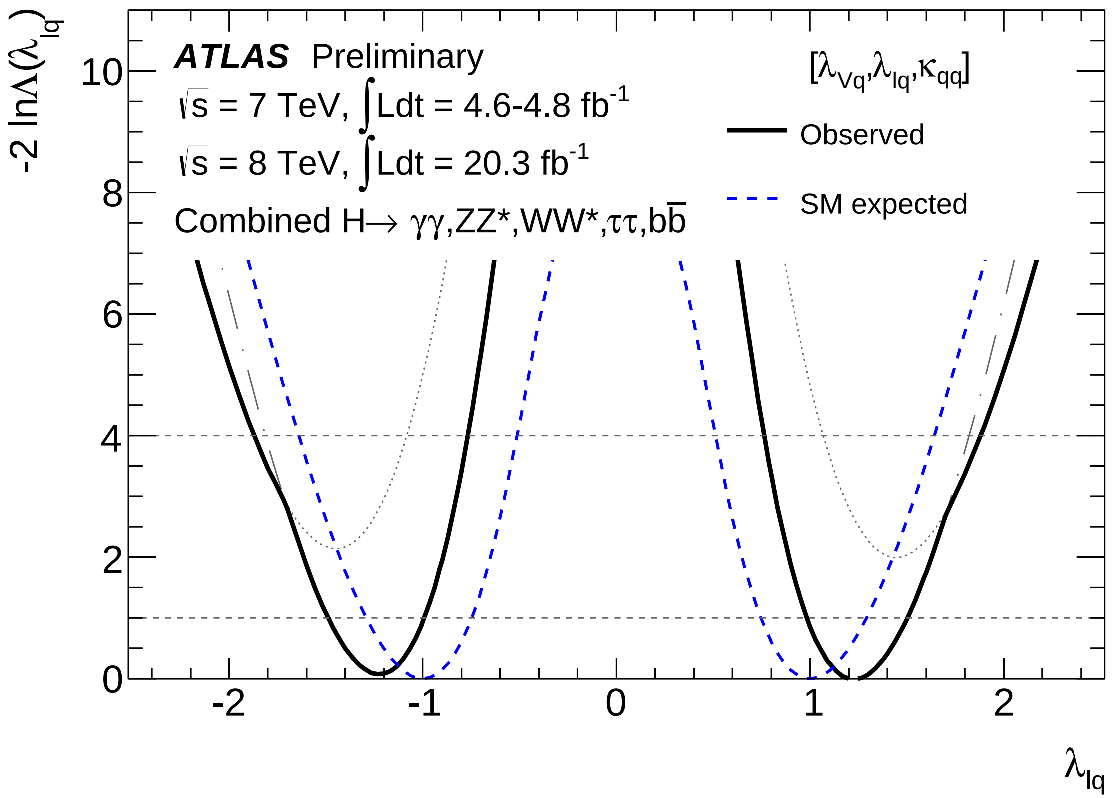
Free Total Width

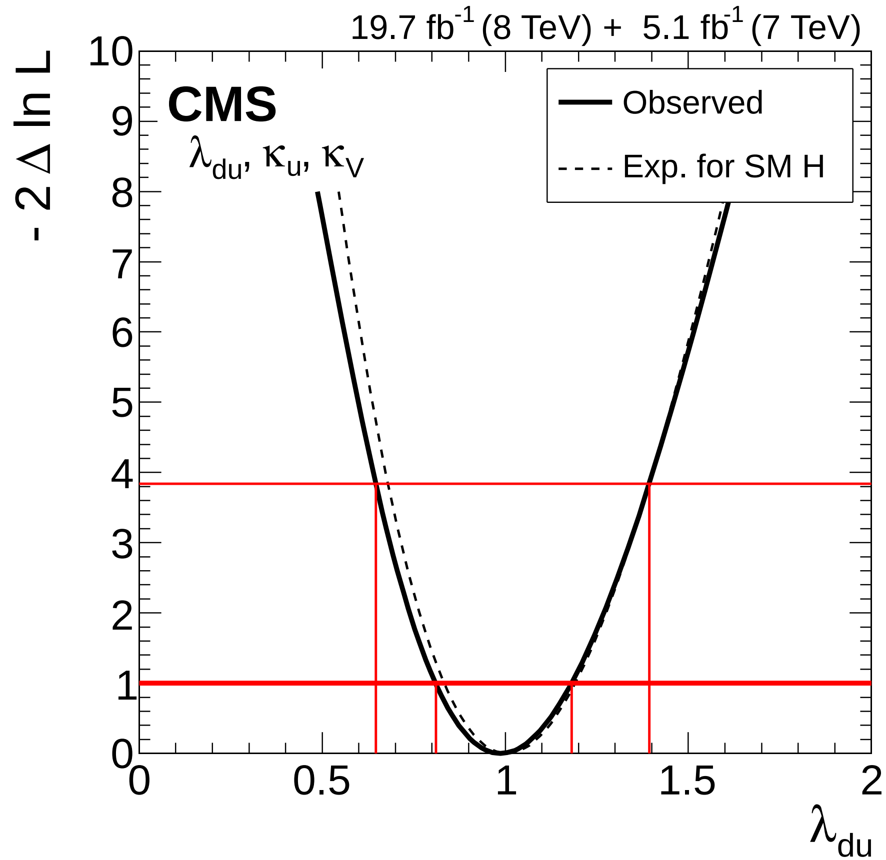




- $\sigma(gg \to H) \cdot \mathcal{B}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \kappa_\gamma^2 \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})}{0.085\kappa_g^2 + 0.0023\kappa_\gamma^2 + 0.91}$
  - Profile κ_g and κ_γ
- ATLAS 95%: $\mathrm{BR}_{\mathrm{inv.}}^{\mathrm{undet.}} < 0.41$
- CMS 95%: $\mathrm{BR}_{\mathrm{inv.}}^{\mathrm{undet.}} < 0.32$

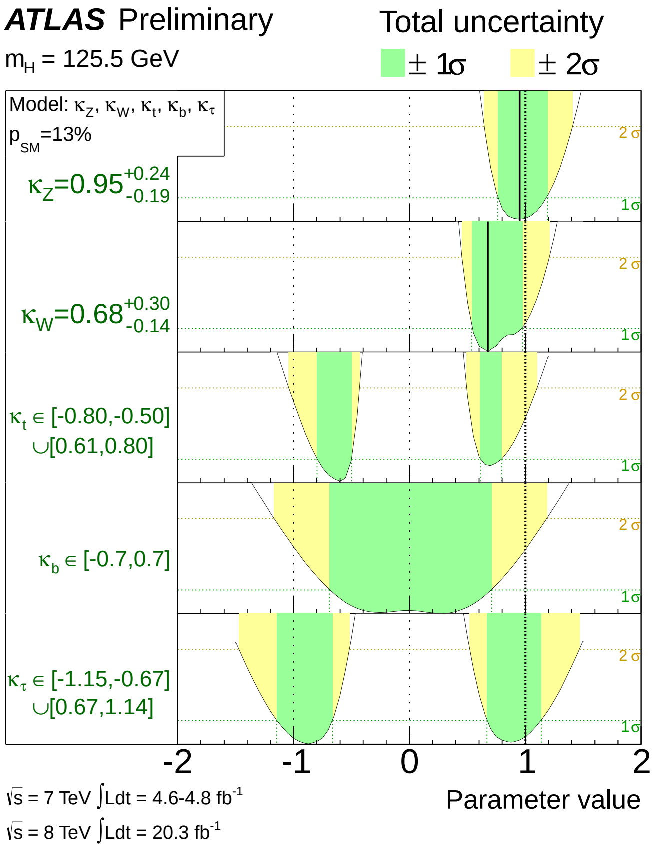
Fermion Symmetries

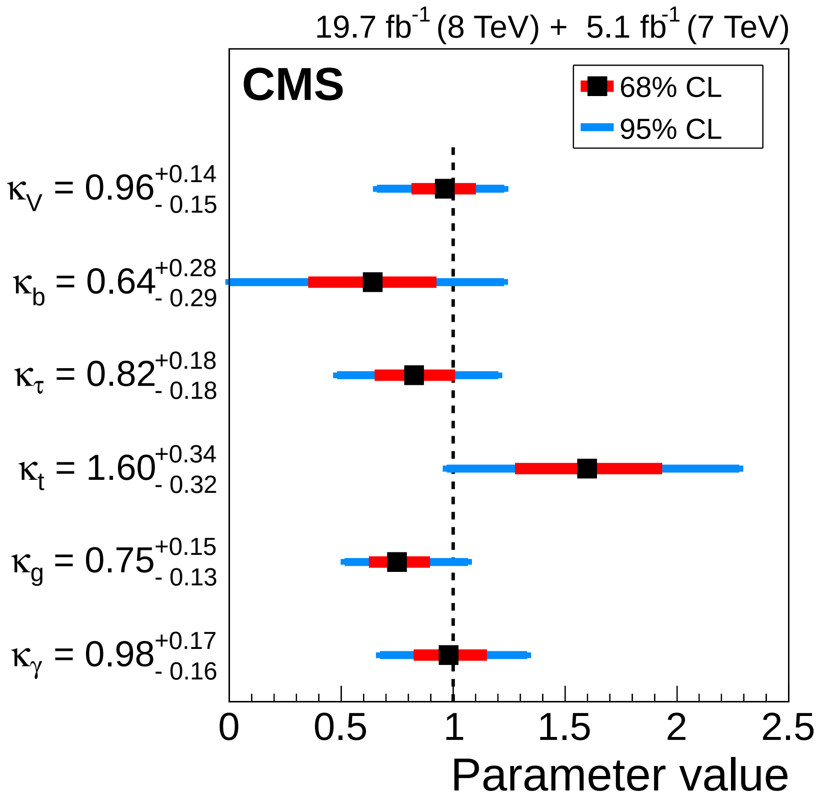




- Fermion symmetries are also tested and are compatible with SM at both experiments
  - Test ratios of couplings to up- and down-type quarks
  - Test ratios of couplings to leptons and quarks

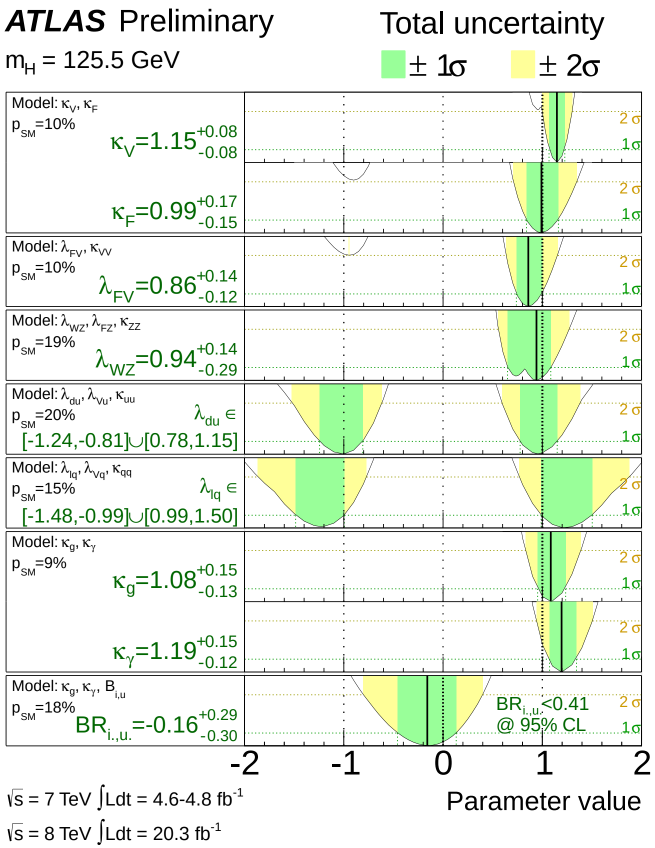
Generic Models

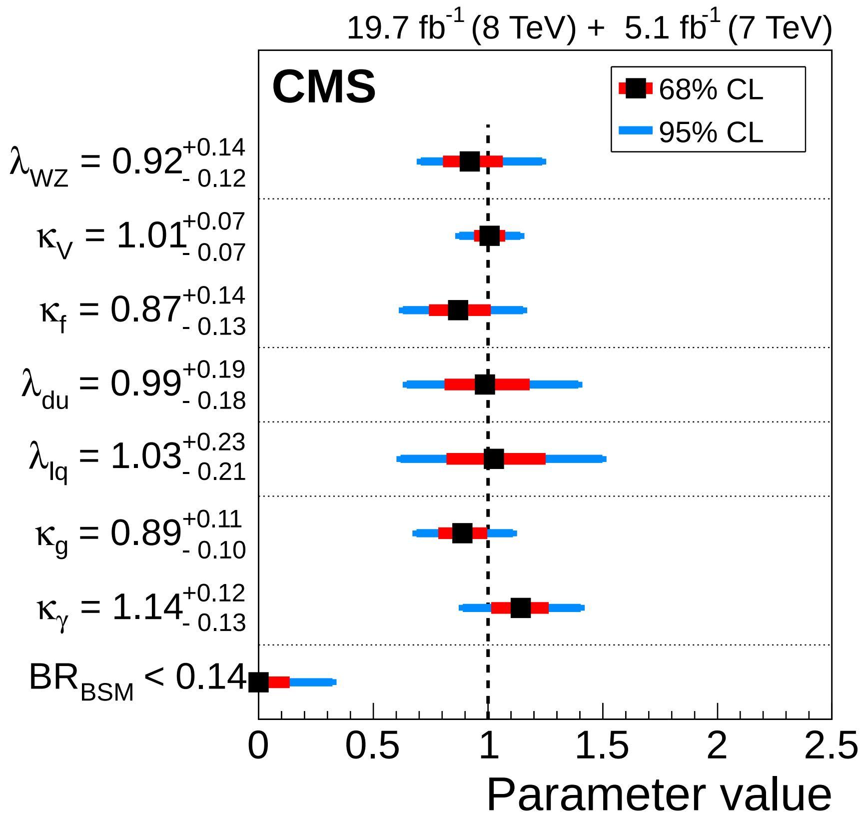




- Test for generic models by allowing all primary couplings to float
- 13% (28%) compatibility with SM in ATLAS (CMS)
  - Largest correlated deviation is $\sim 1.5\sigma$ low κ_b

Results Summary





- Summary of benchmark coupling studies
- Most parameters measurable within 10-30% with current dataset, with no significant deviations
- Work underway to move past LO coupling model

References

- ATLAS Couplings: https://cds.cern.ch/record/1670012/files/ATLAS-CONF-2014-009.pdf
- ATLAS Mass: http://arxiv.org/pdf/1406.3827v1.pdf
- ATLAS Off-shell: http://arxiv.org/abs/1503.01060
- CMS Mass and Couplings: http://arxiv.org/pdf/1412.8662v1.pdf
- CMS Off-shell: http://arxiv.org/pdf/1405.3455.pdf